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# Degeneracy between primordial tensor modes and cosmic strings in future CMB data from the Planck satellite

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While observations indicate that the predominant source of cosmic inhomogeneities are adiabatic perturbations, there are a variety of candidates to provide auxiliary trace effects, including inflation-generated primordial tensors and cosmic defects which both produce B-mode cosmic microwave background polarization. We investigate whether future experiments may suffer confusion as to the true origin of such effects, focusing on the ability of Planck to distinguish tensors from cosmic strings, and show that there is no significant degeneracy.

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## I. INTRODUCTION

Cosmological probes are reaching a sensitivity where they are able to meaningfully constrain models of the early universe. Data compilations including the Wilkinson Microwave Anisotropy Probe five-year (WMAP5) data [1] already indicate that the dominant source of inhomogeneities are primordial adiabatic scalar perturbations [2]. However, there remains room for low-level contributions from other sources, for instance isocurvature perturbations, and the discovery of such trace effects may be essential to enhance the limited information available via the adiabatic scalars. Of particular interest are primordial tensor perturbations, believed to be generated by inflation alongside the scalars, and also cosmic defects.

Cosmological data may even be able to constrain string/M theory, the current dominant unification paradigm. There have been attempts to try to get direct information about string theory from cosmology. For example, it may be possible to infer the topology and geometry of the Calabi-Yau space in which the extra dimensions are compactified [3]. Without going into the model-dependent assumptions, a fairly general prediction from string cosmology seems to be that the level of primordial gravitational waves, given by the tensor-to-scalar ratio  $r$ , is very low ( $r \ll 10^{-3}$ , in some cases even  $r \sim 10^{-23}$ ); as emphasized by Kallosh *et al.* [4] there is no known inflationary model coming from string theory which predicts measurably high primordial tensor modes. Thus, a future detection of  $r$  in the accessible range  $r \gtrsim 10^{-2}$ – $10^{-3}$  would present a tough challenge for string cosmology.

Another typical prediction of string cosmology is the production of cosmic strings [5]. These strings can be fundamental strings or D1 branes (or D-branes with  $D - 1$  dimensions wrapped in the extra dimensions) left over from brane inflation. Alternatively it can be argued that D-term strings are the low-energy effective cousins of D-strings [6]. The dynamics of a system consisting of F- (fundamental) and D-strings is an evolving field [7], and

more study is needed to have a consistent picture of such a network.

Strings produced after inflation [8] will also generate cosmic microwave background (CMB) anisotropies [9–11], which can be parametrized by an amplitude  $G\mu$ , where  $G$  is the gravitational constant and  $\mu$  is the string tension. This poses the question: in the event of a future CMB experiment detecting some “extra” ingredient beyond a primordial (scalar) inflationary spectrum, would its identification as inflationary tensors be secure, or might cosmic strings have generated a signal mistaken as primordial tensors? The interpretation of future observations is clearly contingent on being able to make the right model assumptions in fitting to data. The aim of this paper is to answer this simple question for the specific case of the Planck satellite, due to be launched within the next year.

We remind the reader that both tensors and strings produce a “primordial” B-mode polarization spectrum [12,13], with fairly different spectra. Unlike the other CMB spectra, these are not subdominant to that from the primordial scalars, which is generated only indirectly through lensing of E-modes into B-modes. In principle, ground-based and suborbital B-mode experiments would be more sensitive to both tensors and strings. For example, a null detection by CLOVER would give very tight constraints on the amount of strings possible [13]. Nevertheless, the launch of Planck is imminent and we will show that Planck alone is enough to answer our question in a fairly definitive manner.

## II. METHOD

In order to investigate the possible degeneracy between tensors and cosmic strings, we created simulated Planck data for a few different cosmologies. We include the temperature (TT) and E- and B-mode polarization spectra (TE, EE, and BB) from three temperature channels with specification similar to the HFI channels of frequency 100 GHz, 143 GHz, and 217 GHz, and one 143 GHz polarization

channel, following the current Planck documentation [14]. We use a fiducial model close to the WMAP best-fit flat  $\Lambda$ CDM model, with  $\Omega_b h^2 = 0.022$ ,  $\Omega_c h^2 = 0.105$ ,  $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\tau = 0.09$ ,  $n_s = 0.96$ , and  $A_s^2 = 2.35 \times 10^{-9}$ . The parameters  $r$  and  $G\mu$  take on various values. The likelihood is constructed assuming a fractional sky coverage of 0.8, and up to a maximum multipole of 2000. We use CosmoMC [15] to obtain parameter confidence contours.

The CMB anisotropies created by cosmic strings were also included in the simulated data. For this we use the results from Refs. [10,13],<sup>1</sup> for both temperature and polarization. These CMB anisotropies are obtained from a field-theoretical approach to cosmic strings, simulating the Abelian Higgs model on a lattice. The energy-momentum tensor corresponding to the cosmic strings is extracted and its unequal time correlators (UETCS) computed [17], and then a modified version of CMBeasy [18] yields the CMB power spectra. We follow Ref. [19] and use this subdominant string contribution calculated at only a single cosmology, which gives a negligible degradation of the likelihood values we obtain.

In the end this string contribution, scaled by an amplitude  $G\mu$ , is simply added to the other spectra. In turn,  $G\mu$  can be related to  $f_{10}$ , which measures the fractional contribution of strings to the total TT power spectrum at multipole  $\ell = 10$ . Previous work [9,20] constraining the amount of cosmic strings allowed from current CMB data [21] suggests that not only is a fair amount of string allowed, but actually about 10% of strings is preferred [16] ( $f_{10} \sim 0.1$ ,  $G\mu \sim 0.8 \times 10^{-6}$  in the Abelian Higgs model) by a  $\Delta\chi^2 = -3.5$ . Using Bayesian evidence for model comparison, a logarithmic evidence difference of  $1.8 \pm 0.2$  is obtained between a model with strings with fixed  $n_s = 1$ , and the concordance model. In this sense, we may say that strings are preferred to tilt by the CMB data.<sup>2</sup> Allowing  $n_s$  to deviate from unity, including constraints from big bang nucleosynthesis [22] and the Hubble Key Project [23] all reduce the case for strings: an upper bound of  $f_{10} < 0.10$  on the fraction of power due to strings is obtained.

We show the contributions to the temperature and polarization power spectra coming from inflation, strings, and tensors in Fig. 1, based on Ref. [13]. The normalizations of these three components are free parameters and in this figure are chosen as follows: the normalization of the inflationary scalar component is chosen to be the one that matches current CMB data without including strings or

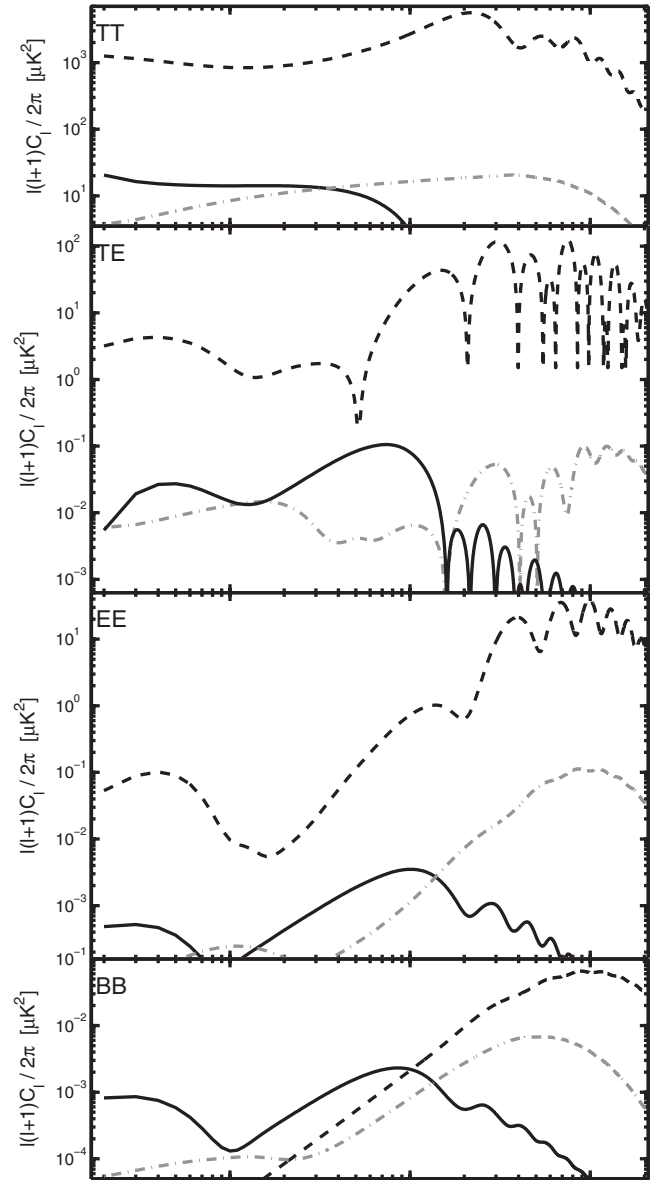


FIG. 1. The CMB temperature and polarization power spectra contributions from inflationary scalar modes (black, dashed), inflationary tensor modes (black, solid), and cosmic strings (gray, dotted-dashed) [13]. The inflationary tensors have  $r = 0.04$  while the string contribution has fractional power at  $\ell = 10$  of  $f_{10} = 0.01$ .

tensor modes. The string contribution is set at the  $f_{10} = 0.01$  level and the inflationary tensor mode normalization corresponding to a tensor-to-scalar ratio of  $r = 0.04$  (at comoving wavevector  $k_0 = 0.01 \text{ Mpc}^{-1}$ ).<sup>3</sup> These levels of  $f_{10}$  and  $r$  are the typical values we will use in our analysis. Tensors and strings are subdominant in the TT, TE, and EE

<sup>1</sup>References [10,13] employed a code in which a bug has been discovered, and this had a small effect in Ref. [16] since it used their results directly (see the respective errata). Here we have used the corrected power spectra from Refs. [10,13] and quote the corrected results from Ref. [16].

<sup>2</sup>Our calculations predated the release of the 5-year WMAP data.

<sup>3</sup>We define  $r$  following the convention of the WMAP papers.

cases (where the data is more constraining), and it is due to this subdominant nature that one may wonder whether Planck data will be able to distinguish between them. By contrast, both tensors and strings dominate in the BB case, whereas (scalar) inflationary modes only enter through lensing.

We simulate data for a set of different cosmologies, varying the amount of primordial tensors  $r$  and cosmic strings  $f_{10}$ . The values of  $r$  chosen for the fiducial cosmologies lie towards the upper bound of detection of Planck, rather than the values of  $r \sim 10^{-23}$  that string theory seems to suggest. If Planck does detect some extra ingredient beyond the standard (scalar) concordance model, the parameter values that would be inferred are at the same level as the ones considered in this article.

### III. RESULTS AND DISCUSSION

Figure 2 shows constraints on tensors and strings when both these components were fitted for in three different choices of input cosmology. They show that there is no significant correlation or degeneracy between the two components; the anticorrelation between  $r$  and  $f_{10}$  is just a few percent. Accordingly, Planck's ability to measure  $r$  is not degraded by allowing the possibility of strings, and vice versa. (Here and throughout the other parameters being varied are the matter and baryon densities, the angular distance to rescattering, the reionization optical depth, the scalar spectra index, and the amplitude of primordial density perturbations.)

This exercise showed that trying to fit the fiducial cosmologies with the correct parameters is very successful, and no degeneracies are found. However, let us suppose that the actual cosmological model includes some signal from cosmic strings, but we only try to fit the data with a model with tensors, or vice versa for the case where the true model has gravitational waves and no strings. Will Planck data be good enough to show that we are trying to fit with the wrong set of parameters?

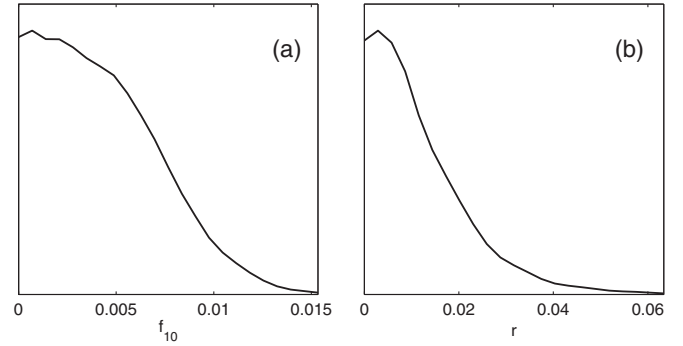


FIG. 3. Marginalized 1D distribution (a) for  $f_{10}$  obtained for a fiducial model with  $r = 0.04$  and no string component (b) for  $r$  obtained when the fiducial model has an  $f_{10} = 0.01$  and no tensors component. The plots show that fitting for only the wrong component does not result in any detection but only upper limits.

In order to answer that we created a fiducial model with tensors  $r = 0.04$  and no strings and tried to fit it with a model with no tensors but strings. In this case (Fig. 3) no strings are detected: instead, upper limits are obtained on  $f_{10}$  similar to, but weaker than, those obtained when we fitted for both components for this same true model (see Table I). Similarly, the results of the true model being  $r = 0$  and  $f_{10} = 0.01$ , but fitting for just  $r$ , are shown in Fig. 3. Once again, no  $r$  is detected and upper limits are obtained. We conclude that one detection will not be mistaken for another.

To determine whether most of the string detection capability comes from Planck's temperature or polarization spectra, we did a similar analysis using data from only some of the power spectra. First we chose not to use BB data. The only appreciable difference is that the value of  $r$  is less constrained. However, there is still no degeneracy between tensors and strings.

We then also performed the analysis using only temperature data. We find that temperature and polarization

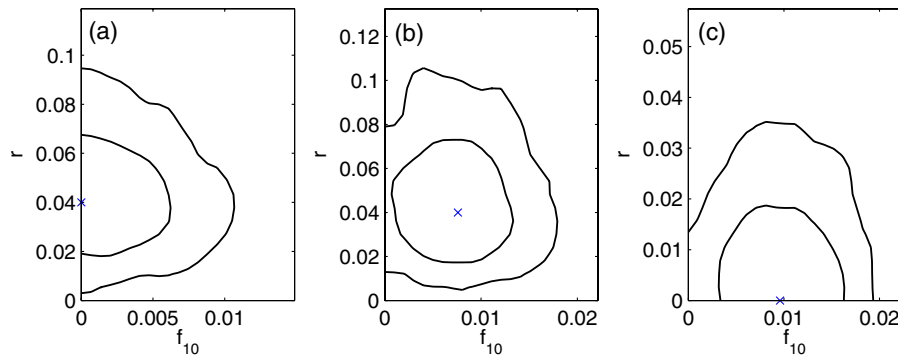


FIG. 2 (color online). 68% and 95% contours of the marginalized 2D posterior distribution for a cosmological model with (a)  $r = 0.04$  and no string component, (b)  $r = 0.04$  and  $f_{10} = 0.008$ , and (c)  $f_{10} = 0.01$  with no tensor component. The actual models are depicted with a cross.

TABLE I. First two rows: values of  $f_{10}$  obtained when trying to fit a fiducial model with tensors  $r = 0.04$  and no strings. Last two rows: values of  $r$  when trying to fit a fiducial model with strings with  $f_{10} = 0.01$  and no tensors.

	Mean	Stand. dev.	68% upper bound	95% upper bound
Fitting for $f_{10}$ only	0.0043	0.0029	0.0056	0.0098
Fitting for both $f_{10}$ and $r$	0.0033	0.0026	0.0041	0.0084
Fitting for $r$ only	0.012	0.010	0.015	0.033
Fitting for both $r$ and $f_{10}$	0.011	0.0091	0.013	0.029

offer similar constraining powers. However, with only temperature there is a positive degeneracy between the scalar spectral index  $n_s$  and  $r$  and a negative degeneracy between  $n_s$  and  $f_{10}$ . These degeneracies go away upon adding polarization data. This implies that the current ambiguity that exists between whether the WMAP data should be interpreted as providing evidence for  $n_s \neq 1$  or for strings will not remain when polarization data improve.

#### IV. CONCLUSIONS

Our analysis shows that at Planck sensitivity there is no significant degeneracy between tensors and cosmic strings. When a set of cosmological data are fitted using both components, the true input value of any component is correctly recovered if it is detectable. If only one component is fitted and it is the wrong one, then it is not detected nor misidentified, and upper limits are found similar to, but

weaker than, in the case when both components are fitted. These weaker bounds are obtained because larger amounts of the wrong component are required because the other is not being fitted. With actual data, one would carry out a Bayesian model selection analysis to assess which was the preferred model to fit, and derive upper limits using Bayesian model averaging as in Ref. [24].

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